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SURFACE STRESS ESTIMATION FOR STUDY OF THE CIRCULATION DYNAMICS--ETC(U)
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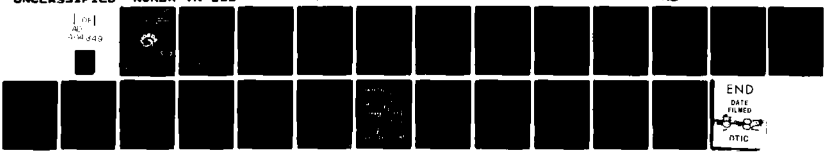

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Naval Ocean Research
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NSTL Station, Mississippi 39529

Surface Stress Estimation for Study of the Circulation Dynamics of the Gulf of Mexico

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Preface

As part of the Reserve Officer Training Program, LCDR J. V. Ramsdell (ONR/NRL TAC 522) participated in a research program with scientists of NORDA Code 322. The study involved an investigation of the availability of wind data over the Gulf of Mexico for application to numerical ocean models. Although synoptic (spatial resolution ~ (100km), temporal resolution ~ 0 (hours)) data is crucial for calculating wind stresses and wind stress curls required by ocean forecasting models, the observational network is presently grossly inadequate over most of the world's oceans. In the Gulf of Mexico there is some hope of obtaining a wind field useful for driving a numerical model. The combination of ships, NOAA permanently anchored meteorological buoys, coastal stations, and initialization data from the National Meteorological Center's limited fine-mesh atmospheric models are all potentially useful. This report includes an evaluation of the available wind data over the Gulf of Mexico, its utility for ocean modeling, and possible unconventional sources of additional wind data.

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ABSTRACT

This report presents the results of a literature search concerning estimation of wind stress over large bodies of water and an evaluation of several sets of stress estimates for the Gulf of Mexico. Wind stress can be estimated directly from wind observations or indirectly from atmospheric pressure by using the pressure gradients and the geostrophic relation. In regions where wind data are sparse, as in the Gulf of Mexico, the use of the indirect method is more practical.

The major problems considered in stress estimation are: treatment of the drag coefficient that relates wind to stress, spatial and temporal averaging of the data before and after making stress estimates, and empirical corrections to be applied to winds computed from pressure gradients. The literature cited indicates that the drag coefficient should be a function of wind speed, rather than a constant as it has been treated historically. The drag coefficient is also a function of atmospheric stability, but this dependency is of secondary importance. To properly resolve the features of the circulation in the Gulf, it will be necessary to estimate stress on at least a daily basis with a minimum spatial resolution of 1^{o} in latitude and longitude. The ageostrophic corrections to wind speed and directions computed from pressure gradients are primarily a function of atmospheric stability and should be determined in the vicinity where they are to be applied. They are secondarily a function of latitude, and the ageostrophic correction to wind direction may also be a function of wind speed.

Two sets of wind stress estimates are currently being used for studies of circulation in the Gulf of Mexico, one set compiled by Elliott (1979) and the other by Blaha and Sturges (1978). Elliott's set contains seasonal averages from shipboard data and is not a time series in the normal sense. Blaha and Sturges' set contains monthly averages derived from surface pressure fields and is a time series - but a constant drag coefficient and questionable ageostrophic corrections were used in making the stress estimates. Both sets are inadequate in their spatial and temporal resolution for detailed investigations of circulation dynamics.

A new set of wind stresses for the Gulf should be calculated from the surface pressure fields used in the initialization of the limited-fine-mesh (LFM) atmospheric model. This data, calibrated by observed winds from the NDBO moored buoys, offers the best hope of determining the wind stress forcing function for driving numerical models of Gulf circulation.

1. Introduction

The influence of wind on the circulation in the Gulf of Mexico has been the subject of a number of investigations inlcuding Franceschini (1953), Smith (1977), Blaha and Sturges (1978), and Elliott (1979). The results of these investigations are generally in agreement, but there are some notable differences. Specifically, there is still uncertainty about the effect of wind on the circulation in the southwestern Gulf, the region for which the least data are available.

This report documents the results of a search of the literature related to the computation of wind stress on the ocean surface, and evaluates meteorological data sets available for use in numerical modeling studies of the Gulf. In particular, available data sets are evaluated for use with the ocean model of Hurlburt and Thompson (1980). Specific data sets evaluated include those of Blaha and Sturges (1978) and Elliott (1979).

The present Hurlburt-Thompson model is a primitive equation model with a 1600km by 900km domain and a horizontal grid spacing of about 20km. The irregular geometry of the Gulf has been included in some of the numerical experiments with driving solely due to forced inflow through the Yucatan Straits and outflow through the Florida Straits. The meteorological input required for model execution is a time series of the surface wind stress field. Useful temporal resolution in the field is limited primarily by the frequency of meteorological observations. Theoretically, the limit to useful spatial resolution is related to grid spacing, but again the practical limitation lies in the available data. Meteorological observations in the region of the Gulf are generally sparse. It is tempting, and in many instances appropriate, to average the available data to compensate for the sparseness and infrequency of the observations. This is the approach followed by Blaha and Sturges and by Elliott. However, averaging degrades the resolution of the data.

DiMego, Bosart, and Endersen (1976) present a climatological analysis of frontal activity in the Gulf in which there is a relatively strong maximum in the number of frontal passages during winter months. The duration of frontal activity associated with each system is of the order of one to two days. Frontal activity is likely to be associated with the highest wind speeds and stresses and with a relatively high degree of atmospheric stability near the surface. These factors indicate that high resolution will be required spatially and temporally for driving a model of the Gulf to statistical equilibrium. It also indicates that incorporation of stability effects may be important in studies of Gulf circulation. The presently available wind data must be evaluated in view of these dominant space and time scales of the atmospheric wind forcing and the minimum requirements necessary for driving an eddy-resolving model of the Gulf circulation.

2. Wind Stress Estimation

The wind stress field can be estimated directly from a wind velocity field using the bulk aerodynamic relationship.

$$\vec{\tau}_{(x,y)} = \rho\, C_D\, |\vec{V}|\, \vec{V} \tag{1}$$

where $\vec{\tau}$ is the stress, ρ is the density of air, $\vec{V}$ is the wind velocity and C_D is a drag coefficient. The reference height for C_D must coincide with the height at which the wind velocity is observed. Alternatively, the stress can be computed from a pressure field using established relationships between pressure gradients and the wind velocity. In the following discussion we will examine both methods for estimating the wind field and the drag coefficient.

Air density will be assumed to be constant, because normal density variations are small compared to the variations and uncertainty in either C_D or $\vec{V}$. This assumption is standard practice in the literature, although Hellerman (1967, 1968) treats the density as a function of latitude. His expression is

$$\rho = (1.136 + .0022\ \phi) \times 10^{-3}\ \mathrm{g\ cm}^{-3} \tag{2}$$

where ϕ is the latitude. It may be reasonable to include this variation in computation of stresses in the Gulf because of its systematic nature.

Ideally, the stress field should be computed directly from a set of simultaneous wind observations distributed throughout the region of interest. As a practical matter, for large regions in the Gulf of Mexico, this approach is not realistic. The available data are sparse and in many areas represent infrequent wind observations. Two alternatives to the direct use of the available wind data exist. The first is the use of spatially and temporally averaged data. Franceschini (1953) and Elliott (1979) have chosen this alternative, with its inherent loss of resolution. Franceschini's resolution

is limited to 2^{o} squares and temporally limited to monthly averages, while the resolution of Elliott's data are 1^{o} squares and seasons. The second alternative is to estimate the wind at grid points from streamline and isotach analyses. However, this alternative is less attractive because these analyses are not routinely made for surface winds. No examples have been found for the Gulf.

The second method of estimating the wind stress field involves the use of surface pressure patterns to estimate the wind velocity field. In this method the surface wind velocity is assumed to be composed of geostrophic and ageostrophic components. The geostrophic component results from a balance between the Coriolis and pressure gradient forces and is computed from

$$\vec{V}_g = \hat{k} \times \frac{1}{\rho f} \nabla_h P \qquad (3)$$

where $\vec{V}_g$ denotes the geostrophic wind, $\hat{k}$ is a unit vector in the vertical, f is the Coriolis parameter, and $\nabla_h P$ is the horizontal pressure gradient. Computation of geostrophic winds is straightforward, given routine surface pressure analyses. Surface pressure analyses are standard products of the National Weather Service and are prepared at three hour intervals.

3. Ageostropic Wind Corrections

Implicit in the geostrophic approximation are assumptions that surface friction, isobaric curvature and time variation of the wind are negligible. The ageostrophic component of the wind vector arises from departures from these assumptions. Except for the curvature term, rather than attemping to compute the ageostrophic component directly, it is standard practice to apply empirical correction factors independently to the geostrophic speed and direction. Typical corrections are a 20 to 40% reduction in speed and a 15^{o} counter-clockwise rotation of the wind direction. There are relatively strong theoretical arguments that indicate that these correction factors should be functions of wind speed, atmospheric stability and latitude.

Clarke and Hess (1975) and Larson (1975) give models for both corrections. Larson's wind speed correction model is a function of only latitude, and the direction correction is a function of latitude and wind speed. The correction models of Clarke and Hess are more sophisticated, incorporating all 3 factors.

In the latitude band between 20^{o} to 30^{o}, which includes the Gulf of Mexico, the wind direction correction angle increases toward the equator, in all models. For neutral atmospheric stability and a 10 ms^{-1} wind speed, the correction at 25^{o} latitude is 2^{o}. The total change in correction angle across the band is 3^{o} to 5^{o}. Based on the model of Clarke and Hess, the effect of atmospheric instability is to decrease the magnitude of the correction at all latitudes. The decrease is larger at higher latitudes than at low latitudes.

At 30^{o} latitude the Clarke and Hess model for neutral atmospheric stability and the Larson model both indicate that the ratio between the surface and geostrophic wind speeds is about .85. As the equator is approached this ratio decreases. In Larson's model the decrease is much less pronounced than in the model of Clarke and Hess. As might be expected, the effect of increasing atmospheric instability is to increase the ratio between the speeds, i.e. to decrease the correction required.

Comparisons between observed surface and computed geostrophic winds (e.g. Roll, 1965; Aagaard, 1969 and Larson, 1975) provide graphic evidence that the single set of correction factors will not permit accurate estimates of the surface wind in all conditions. However, they do indicate that it is reasonable to apply an average correction. Further, data in Roll (1965) and Aagaard (1969) indicate that the effects of atmospheric stability are significant and should be included in the average correction factor. In essence, this means that the correction factors should be time dependent.

4. Drag Coefficient

In the derivation of the bulk aerodynamic relationship between wind and the surface stress, it is generally assumed that the drag coefficient is a constant. However, it has clearly been established that this is not the case. Rather, the drag coefficient is a function of both wind speed and atmospheric stability. The relationship between C_D and wind speed was postulated by Charnock (1955) on the basis of theoretical considerations, and has been convincingly demonstrated in summaries of data compiled by Smith and Banke (1975) and Garratt (1977).

In his summary of data on the drag coefficient, Garratt provides the following expressions relating C_D and wind speed for neutral atmospheric conditions (in m sec $^{-1}$)

$$C_D = 0.51\ V^{0.46} \times 10^{-3} \tag{4}$$

and

$$C_D = .75 + 0.067\ V \times 10^{-3} \tag{5}$$

Either relationship can be supported by the data, but the linear form is more consistent with expressions proposed by others.

Sethuraman (1979) was unable to find a consistent relationship between C_D and speed. It appears likely that this inability was the result of a limited range of wind speeds included in his data base. However, he did find a variation of C_D with wave characteristics that he associated with wind direction and ocean surface in the upwind direction. As might be expected, he found C_D increased with the roughness of the sea.

Fissel, Pond and Miyake (1977) have explored the effects of incorporating a wind speed variation of C_D in stress computations for the North Pacific Ocean. Replacing a constant C_D with one linearly related to speed increased the magnitude of the stresses, but did not significantly alter their direction. This result is reasonable, and would be expected for locations where high wind speeds are associated with either a relatively narrow range of directions or

are approximately evenly distributed over all directions. However, extrapolation of this result to other locations, without further verification or knowledge of the joint frequency distribution between wind direction and speed, would be open to serious question.

The effects of atmospheric stability of C_D have been discussed in some detail in the literature (e.g. Roll, 1965; Deardorff, 1968 and Arya, 1977). In summary, the effect of increasing instability is to increase C_D, and the effect of increasing stability is to decrease it. Deardorff provides a theoretically derived, approximate empirical correction for C_D based upon a bulk Richardson number that can be computed from the air and sea temperatures, the wind speed, specific humidity and the height of the meteorological observations. Using these corrections, the magnitude of C_D may be increased by 30% in unstable conditions and decreased by 50% or more in stable conditions when compared with its neutral value.

The combined effect of wind speed and stability on the drag coefficient is discussed by Liu, Katsaros and Businger (1979). At low wind speeds, the stability effects are dominant, but as the speed increases they rapidly become negligible. Because of the non-linear relationship between wind speed and stress, it is unlikely that the inclusion of the stability variation of C_D would have a significant effect on computed wind stresses. This conclusion is confirmed, in part, by the calculations of Saunders (1977), who showed seasonally averaged stresses that were relatively unaffected by consideration of stability effects on the drag coefficient. Saunders noted that incorporating stability in the C_D formulation approximately doubled the time required for computation of stresses.

5. Spatial and Temporal Averaging

The non-linearity between wind velocity and stress precludes computation of the average stress from the average wind speed. Stresses should be computed prior to averaging. The importance of the stress computation and averaging in the proper order has been recognized in the oceanographic literature for some time. Aagaard (1970), Veronis (1970) and Welch (1972) have documented the effect of the use of average wind or pressure data on stress computations in which C_D was treated as a constant. More recently, Fissel, Pond and Miyake (1977) have examined the effect of averaging prior to stress computation using both constant and linear drag coefficients.

Aagaard (1970) noted that the qualitative features of the stress field remained intact as the pre-stress computation averaging period increased up to 30 days. But, he concluded that 50 to 80% of the stress was produced by short-term variations in the wind field. He also noted that variations with a period as short as one day could be significant. Similarly, on the basis of modeling studies, Veronis (1970) notes that transient winds were important to the mean circulation in the oceans. His studies indicated that fluctuating features of the stress field with horizontal dimensions 1/4 the scale of the mean features contributed significantly to the total transport in the model.

The results of Welch (1972) and Fissel, Pond and Miyake (1977) are more quantitative. Welch examined the effect of observational frequency on stress magnitudes. Reducing the frequency of observations has about the same effect as averaging. When the stress computations were based on 8 observations or surface analyses a day, the transport response was given a relative value of 1. Decreasing the sampling frequency to one per day, reduced the relative response to about 0.85. Further reduction in the sampling frequency to 0.1 per day resulted in a decreased in response to about 0.25. Approximately the same response was observed with a sampling frequency of one observation per 30 days.

Using 10 year's data from Ocean Ship P, Fissel, Pond and Miyake (1977) have explored the effect of vector averaging wind data before stress computation. Their basic data set consisted of wind observations made at three hour intervals. Table 1 shows the reduction in stress for several averaging periods. It should be noted that the stresses computed using a linear drag coefficient show a somewhat greater reduction than those computed with a constant coefficient. In general the magnitude of stresses computed using a linear drag coefficient were significantly larger than those computed using a constant value. The increase was about 50% during winter months and decreased to a minimum of about 15% in the summer. As a result the use of the linear drag coefficient enhances seasonal variations in stress.

In a matter related to averaging of data, Veronis (1970) and Saunders (1976) and others have considered the spatial resolution required in stress estimates. Veronis concluded that it is necessary to resolve features of the stress with a horizontal scale of 1/4 the dimension of the mean features. Assuming that the scale of the mean stress features of the Gulf of Mexico is 1000 km, it is necessary to be able to resolve features with horizontal dimensions of the order of 250 km. This requires that data be input on a grid with maximum spacing of 125 km, or about 1°. Certainly near the coastal zones during sea breeze events this resolution is inadequate. Saunders compared estimates of the wind stress curl based on data spacing of 1° with estimates based on spacings of 5° and 10°. He found that the coarser spacing resulted in reductions of the curl magnitude by about 50%.

Averaging Period	Stress Reduction in Percent	
(Days)	Constant C_D	Linear C_D
1	10	15
10	45	55
30	55	70
90	65	75

Table 1. Stress Reduction at Weather Ship P Due to Vector Averaging of the Wind Prior to Stress Computation.

6. Data Set Evaluation

Returning to the consideration of data sets for use in studying the Gulf of Mexico circulation, we will discuss the data sets of Elliott (1979) and Blaha and Sturges (1978) in some detail. The data set of Franceschini (1953) may or may not be available, but suffers from deficiencies that will be noted in the other data sets. The extensive data set of Hellerman (1967) is not considered because of the limited resolution in the Gulf of Mexico.

The data set used by Elliott (1979) consists of seasonally averaged stresses for 1° squares of latitude and longitude. Individual stress estimates were made directly from shipboard wind observations using a drag coefficient linearly related to wind speed with appropriate stability corrections. The individual stress estimates were then averaged in time and space. Temporal averaging was done by season without regard to year. As a result, the data set is not a time series in the usual sense.

The computational procedures followed by Elliott appear to be state-of-the-art and appropriate for his application. However, the temporal averaging process makes the final data set inappropriate for use in the examination of the dynamics of the Gulf circulation. Since it is likely that the maximum useful averaging period for studying dynamics of the circulation would be of the order of a day of two, even if Elliott's data set were a time series, it would not be an appropriate set for the intended application because of the coarseness of the temporal averaging. Welch (1972) expressed a concern about the use of stress computation schemes that do not account for extremes, and more recent studies cited above have supported his concern. These extremes are smeared away during the temporal averaging. In addition, ships naturally avoid wind extremes and thus introduce a bias in the data toward weaker winds.

The Blaha and Sturges (1978) data set, also used by Molinari (1978), consists of monthly average stresses computed from surface pressure data. This data was analyzed according to the technique of Bakun (1973), who used it to calculate coastal upwelling indices off the West Coast of North America. Because the surface pressure data were monthly averages, wind stresses were computed from the resultant wind for the month. Spatially, the stresses represent averages over relatively large areas. The pressure data on which they were computed were on a 3^0 grid. The drag coefficient used was a constant 0.0013. The ageostrophic wind corrections were also assumed to be constant, 0.7 for speed and 15^0 for direction. These constants were obtained by Bakun using data from the West Coast of the United States, not the Gulf.

We reject the Blaha and Sturges data set for the intended application for the following reason. The temporal and spatial resolution in the data are too coarse to be useful in studying circulation dynamics, and the formulation of the drag coefficient and ageostrophic corrections are not appropriate for the Gulf of Mexico. In essence, this data set would not permit adequate representation of the effects of extreme wind velocities during frontal passages and storms which are likely to be important to Gulf circulation dynamics.

7. Conclusions and Recommendations

No surface wind stress data set has been compiled that is consistent with the goal of studying the dynamics of the circulation of the Gulf of Mexico. However, this does not mean that an adequate data base for that purpose does not exist. Surface pressure analyses for the United States generally cover most of the Gulf. The analyses are made 8 times daily. The 1200Z analyses are published weekly, and are available on a subscription basis from the Government Printing Office. Back analyses from 1960 to date are available from the National Climatic Center. The daily Northern Hemisphere analyses for 1200Z are published on a monthly basis and are available back to 1899. The scale of the presentation of these analyses is too large to give much detail in the Gulf. However, they may be useful in supplementing the information on the United States analyses. It may be possible to get these analyses in digital form, otherwise extracting the data may be a lengthy, tedious task. Another possible source of pressure data is the data set used to initialize the NWS limited fine-mesh model. Currently this model extends over the entire Gulf of Mexico. An analysis using assimilated observations plus forecast data as a first guess is conducted every 12 hours for model initialization. Figure 1 is a result of the LFM analysis for 1200Z 19 June, 1981. This data is disseminated through the NOAA facsimile circuit each day to subscribers. Note the domain of the LFM initilization extends over 99% of the area of the Gulf of Mexico, and over all waters deeper than 200 m. The availability and extent of the digital record of these data are still to be determined.

The use of pressure data is a more realistic approach to stress estimation in the Gulf because the number of locations (ships and buoys) reporting observed winds is small and pressure fields are more reliably interpolated than wind fields. It is recommended that the drag coefficient formulation of Garrett

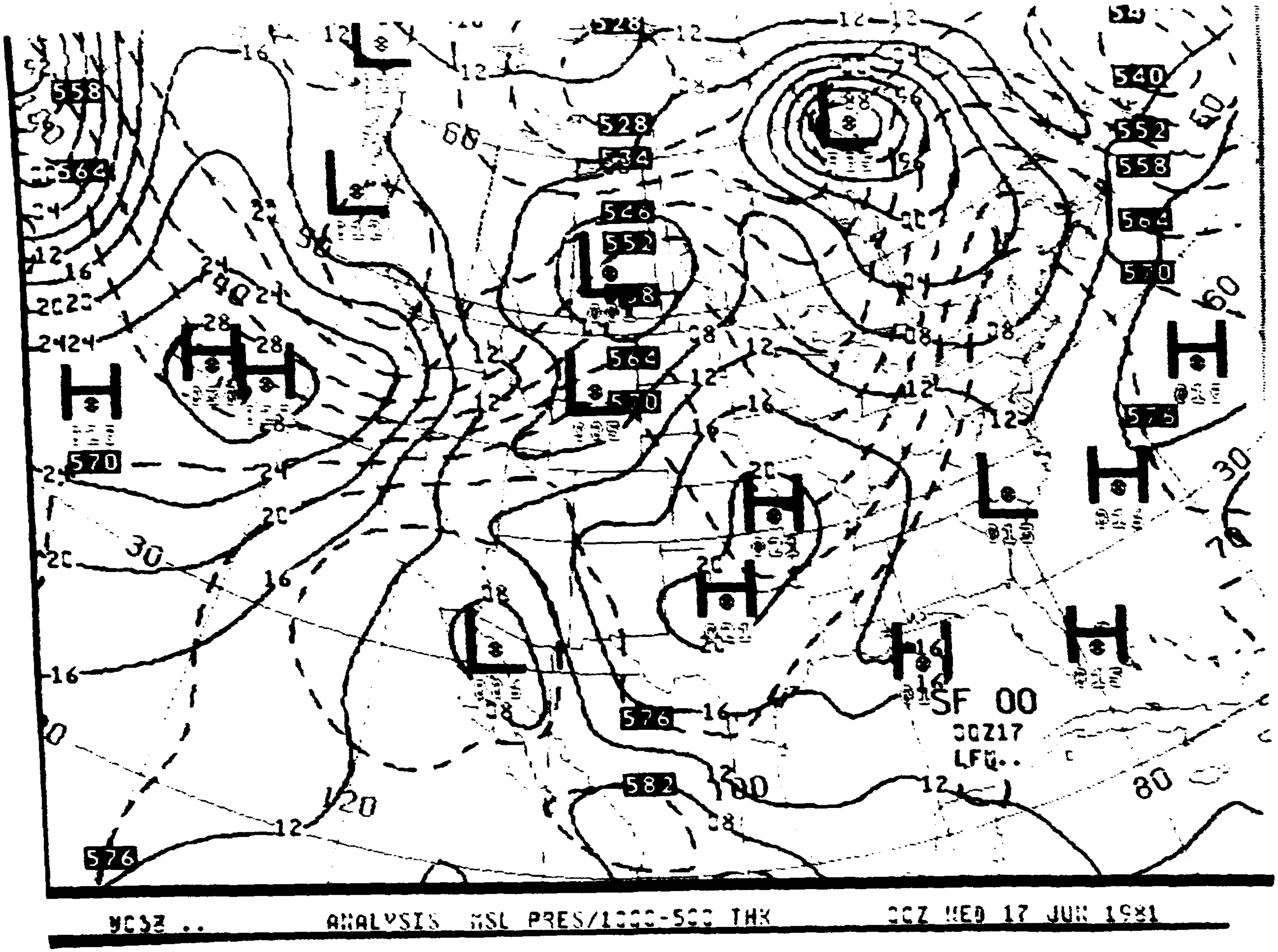

Figure 1: Mean sea level pressure field (solid lines) used as initial data for the limited-fine-mesh atmospheric prediction model of NMC. Contour interval 4 mb.

(1977) or Smith and Banke (1975) be used in estimating stresses from pressure gradients. It is also recommended that the ageostrophic wind corrections be determined form data collected in the Gulf of Mexico, rather than from models derived from data in other areas.

The corrections can be determined by comparing the observed winds at the NOAA data buoys with computed winds. Any wind speed dependence of the corrections should be identified. Stability dependence can be evaluated by examining the relationship of computed corrections and time of year or other stability related variables such as the difference between air and sea temperatures. Any stability dependence identified can then be included implicitly by making the ageostrophic correction a function of time, etc. With respect to systematic variations with latitude, the importance of these variations has not been adequately established to make their inclusion a firm recommendation.

In the long term, satellite derived wind speeds and directions using scatterometers and related instrumentation are essential for driving ocean models. The wind data for SEASAT over the Gulf of Mexico during a portion of 1978 remain to be processed at JPL. We are most interested in obtaining that data set. However, in the short term, surface pressure data for the Gulf of Mexico, calibrated by NDBO buoy winds, offers the best possible data set for determining the wind stress forcing function over the Gulf of Mexico.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a literature search concerning estimation of wind stress over large bodies of water and an evaluation of several sets of stress estimates for the Gulf of Mexico. Wind stress can be estimated directly from wind observations or indirectly from atmospheric pressure by using the pressure gradients and the geostrophic relation. In regions where wind data are sparse, as in the Gulf of Mexico, the use of the indirect method is more practical.

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